

Deconstructing HD 28867

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ABSTRACT

The 3'' pair of B9 stars, HD 28867, is one of the brightest X-ray sources in the Taurus-Auriga star forming region. In this multi-wavelength study, we attempt to deduce the source of the X-ray emission. We show that the East component is the X-ray source. The East component has a near-IR excess and displays narrow absorption lines in the optical, both of which are consistent with a cool stellar companion. This companion is one of the brightest low mass pre-main sequence stars in Tau-Aur; at 2 μm it and the B9 star are equally bright. We see evidence for radial velocity variability in the cool component of $>34 \text{ km s}^{-1}$. It is not visible in K band speckle imaging, which constrains the companion to lie within 14 AU of the B star.

We also report on a possible fourth member of the group, an M1 star 18'' south of HD 28867.

Subject headings: stars: individual (HD 28867); open clusters and associations: individual (Taurus)

1. Introduction

The 3'' visual pair HD 28867 (HR 1442; SAO 94002) is one of the brightest stellar X-ray sources in the Taurus-Auriga star formation region. Hoffleit (1982) lists the spectral type as B9 IVn. Late B stars are not usually bright X-ray sources. That this system is a member of an active star forming region suggests that either young B stars may be bright X-ray sources in some cases, or that the system may hide a less massive but very active pre-main sequence star.

The Hipparcos catalog (ESA 1997) quotes $V = 6.26$ and $\Delta V = 0.05 \text{ mag}$. The

individual V magnitudes are 6.99 and 7.04. The position angle of the pair is 277.1° , with a separation of $3.078''$. The two stars, which we refer to as the East and West components, have a common proper motion, with no significant change in position angle or separation seen in 113 years (Hoffleit 1982). Worley & Douglass (1997) make no mention of a change in position angle or separation in 159 years of observations (1830-1989). The East component is the primary.

HD 28867 is in the vicinity of the L1551 dark cloud, an active part of the Taurus-Auriga star formation complex. In a spectroscopic search for previously unknown weak emission line (wTTS) or Herbig Ae stars, Feigelson & Kriss (1983) failed to note any $H\alpha$ emission associated with this system. The star was, however, detected as a bright X-ray source with the Einstein Observatory Imaging Proportional Counter (IPC) in observation sequences 867 and 10538. Walter et al. (1988) quoted a count rate of 0.12 c s^{-1} . The system was catalogued as MS0430.6+1754 by Gioia et al. (1990), with a count rate of 0.10 c s^{-1} and $\log(f_x/f_v)=-3.62$ (Stocke et al. 1991). It was further detected in the Einstein slew survey (Elvis et al. 1992) as 1ES0430+179 with an IPC count rate of $0.11 \pm 0.03 \text{ c s}^{-1}$. Schmitt et al. (1990) found a coronal temperature of $\log(T)=7.07 \pm 0.08$, with an absorption column $\log(N_H)=20.0$. The 0.2-4.0 keV flux was $2.7 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

Carkner et al. (1996) reported detections of HD 28867 in ROSAT and ASCA observations of the L1551 region. Their spectral fit of the ROSAT PSPC data finds $kT=1.1 \text{ keV}$, $\log(n_H)=20.6$, and $f_x=4.1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3-2.0 keV), with comparable results ($kT=1.2 \text{ keV}$, $\log(n_H)=20.6$, and $f_x=2.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ [0.8-5.0 keV]) from the ASCA data. They show that the X-ray source is variable at $>95\%$ confidence. Berghöfer, Schmitt, & Cassinelli (1996) show that HD 28867 is one of the most X-ray luminous late-B stars in the Yale Bright Star Catalog (Hoffleit 1982).

White, Pallavicini, & Kundu (1992) detected HD 28867 with a 6 cm flux of 0.36 mJy

in a radio survey of selected PMS stars. They were unable to establish which star in the binary system was coincident with the radio source. The radio flux is comparable to that of radio-bright low mass PMS stars in Tau-Aur, and they speculated that the source might be an unseen companion.

This system is IRAS point source 04306+1754. It was detected at $12\mu\text{m}$ with a flux of 0.48 Jy; upper limits on the flux at 25 and $60\mu\text{m}$ are 0.58 and 0.40 Jy, respectively. The system was not resolved by IRAS.

Walter & Boyd (1991) showed that HD 28867 shares the space motion and parallax of the Tau-Aur star forming region. The Hipparcos catalog (ESA 1997) provides a parallax of 7.71 mas (milli-arcseconds), for a distance of 130 ± 23 pc. HD 28867 appears to be an intermediate mass member of the Tau-Aur association, on or near the zero-age main sequence with an age of no more than a few million years. At this distance the X-ray luminosity is about 10^{31} erg s^{-1} , which makes it one of the most X-ray luminous stars associated with the Taurus-Auriga complex. Only HD 283572 (Walter et al. 1987) is more luminous in the Damiani et al. (1995) compilation of Einstein IPC observations of Tau-Aur; none of the T Tauri stars in the ROSAT survey (Neuhäuser et al. 1995) exceed this luminosity. That it is a bright and variable X-ray source, a radio source, and is detected by IRAS at $12\mu\text{m}$, strongly suggests that HD 28867 is more interesting than the typical B9 star. The glare of the bright B stars may hide a lower mass companion, or the young B9 stars themselves may be magnetically active as a consequence of extreme youth. Here we present multiwavelength photometric and spectroscopic observations which clarify the nature of HD 28867.

2. Late B Stars as X-ray Sources

Along the main sequence, the mean f_X/f_{bol} ratio reaches a minimum among the late-B/early-A stars (e.g., Pallavicini et al. 1981). This is consistent with expectations, as these stars lack the strong winds (and resulting shocks) of the most massive stars (but see Feigelson et al. 2002), and lack the deep convection zones which generate and amplify the magnetic fields of the cool stars (Daniel, Linsky & Gagné 2002 provide a more comprehensive review of these issues). While O stars follow the trend $f_X/f_{bol} \approx 10^{-7}$, Cassinelli et al. (1994) show that f_X/f_{bol} decreases monotonically from about 10^{-7} at spectral types B0-B1 to a few $\times 10^{-9}$ at spectral type B3, among stars not known to be multiple. Schmitt et al. (1993) reported detections of three of six late B (B7-B9) primaries in wide visual pairs (resolved in the ROSAT HRI), with $\log(f_X/f_{bol})$ between -6.1 and -4.9, but Schmitt (1997) failed to detect X-ray emission from any of the three A stars earlier than spectral type A7 in a complete sample of stars within 13 pc (there are no B stars in this sample). So while a few late B/early A stars not known to be binaries may be bright X-ray sources, most are not.

A simple way to add excess X-ray flux to late B/early A stars is to provide a lower mass binary companion. Given the main sequence lifetimes of these stars, the cool star is likely to be young and active. Golub et al. (1983) and Caillault & Helfand (1985) were the first to suggest that the X-ray bright late B/early A stars are close binaries with an active cool star. White et al. (1992) suggested this very explanation for the X-ray and radio activity in HD 28867. This would not be the first example of a late B/cool star binary in a star forming region. Casey et al. (1995) showed that the X-ray emitting late B star TY Cra in the CrA star formation region is a triple system, consisting of two lower mass convective stars in addition to the B8-9 primary. The X-ray flux is consistent with that expected from the brightest low mass PMS stars, such as HD 283572 (Walter et al. 1987),

which is approximately the same mass and spectral type as the TY CrA secondary.

Close binary systems are common, and on a statistical basis there is no evidence to support the hypothesis that late B stars in star forming regions are intrinsic X-ray sources: Caillault, Gagné, & Stauffer (1994) showed that the fraction of B star X-ray sources in the Orion Nebula region was just that expected to be close binaries with late-type companions. Feigelson et al. (2002) concur, and show that the X-ray luminosities require F/G type companions, rather than K/M companions. Jefferies, Thurston, & Pye (1997) reach the same conclusion in the NGC 2516 cluster (they also suggest that magnetic chemically peculiar B and A stars are more likely to be detected as X-ray sources than are normal late-B and A stars, either because they are intrinsically brighter or because they are more likely to have a binary companion). Daniel et al. (2002) report that two mid-B and A Pleiads with F-G companions are detected in a CHANDRA observations, while two A stars not known to have cooler companions are not detected.

Based on luminosity functions and hardness ratios, Huélamo et al. (2000) also argue that the bright, hard X-ray sources in unresolved Lindroos (1986) pairs must be late-type companions. Indeed, using diffraction-limited near-IR images, Huélamo et al. (2001) resolved one of three late-B Lindroos systems into the B star and a pre-main sequence K star.

The alternative hypothesis is that HD 28867, a young intermediate mass star, may retain some vestige of primordial magnetic activity, a “naked” Herbig Ae star, so to speak. Zinnecker & Preibisch (1994) show that X-ray luminosities of some of the more extreme Herbig Ae stars, including HR 6000, MCW 10980, and Z CMa, are comparable to that of HD 28867, but HD 28867 is not known to have any of the other spectroscopic characteristics of the Herbig Ae stars. Giampapa, Prosser, & Fleming (1998) argued that two mid-B stars in the Pleiades-age cluster IC 4665 are intrinsic X-ray sources. These stars, with spectral

types B5IV and B6V, are hotter and more massive than the stars in HD 28867.

HD 28867 exhibits a flux ratio $f_X/f_{bol} = 10^{-4.9}$ (Berghöfer et al. 1996) when referenced to the combined light of both stars. This is clearly much larger than expected for a single, non-chemically peculiar B9 star.

3. New Data

In Table 1 we present the positions of the visible stars, taken from the “Double and Multiples: Component Solutions” section of the Hipparcos and Tycho catalogs. We determined absolute positions in the K-band image (Figure 1) by using a reference grid of three stars from the USNO A2.0 catalog (Monet et al. 1998) which were also detected in this image. The HD 28867 pair is unresolved in the USNO A2.0 catalog. We measured the positions of the three components on the K band image, and corrected the coordinates of the South component to the Hipparcos reference frame. The South component is not included in either the Hipparcos or USNO A2.0 catalogs. We also show the position of the radio source from White et al. (1992). This position is epoch 1990.1. We have applied 10 years of proper motion (from the Hipparcos catalog) and precessed the coordinates to equinox J2000. The radio source lies within $0.3''$ of HD 28867E.

3.1. Near-IR Photometry

We obtained JHK images of the system using the CIRIM infrared imager (Elston 1999) on the CTIO 1.5m reflector on 19 February 1997 (Figure 1). We observed using 5 raster positions, one at the center and four each offset by $15''$. The integration time was 0.4 seconds, with three coadds at each raster position. The net exposure time is 6 seconds

per filter. The data were coadded using the DOCIRIM software¹. The plate scale is 0.6'' per pixel.

We observed Elias et al. (1982) flux standards approximately hourly; the photometric solution has an RMS scatter of less than 2% at J and K, and 3.5% at H.

We measured magnitudes using aperture photometry. The standards were extracted using a 20 pixel (12.5'') radius aperture. We generated aperture correction tables using the standard stars. We extracted the the stellar fluxes using 3 pixel (1.9'') apertures centroided on the peak of the flux, and corrected for the light outside the aperture. The background is extracted within an annulus between 8 and 28 pixels. The stellar magnitudes are given in Table 2. We verified that this returned pretty good absolute photometry by extracting the flux from the pair of B stars using a 20'' aperture.

The X-ray column of $10^{20.6} \text{ cm}^{-2}$ corresponds to $A_V=0.21$ mag; the observed $V - K=0.23$ mag of the West component requires $A_V=0.25$ mag if this B9 star has intrinsic colors of 0. These values are consistent within the uncertainties; we adopt $A_V=0.25$ mag, which corresponds to $A_K=0.03$ mag for $R=3.1$. We assume the reddening is interstellar and that both components are equally affected. After correcting for this reddening, HD 28867E shows a significant near-IR excess of 0.18 mag in $J - K$, and a $V - K$ color of 0.6 mag.

In addition to the pair of B stars, four other objects are visible in the near-IR images. The brightest of these is 18'' south of the B stars. The position is coincident with that of a Chandra X-ray source (§3.2.2). The near-IR colors are consistent with an early M spectral type; it could be a either T Tauri star at a projected distance of 2300 AU from the B stars, or a foreground active M dwarf at about 80 pc. We call this HD 28867S. The other three near-IR sources are relatively faint objects in the USNO A2.0 catalog (Monet et al. 1998).

¹<http://www.astro.sunysb.edu/fwalter/CIRIM/cirim.html>

3.2. X-rays

3.2.1. *ROSAT HRI*

We obtained ROSAT HRI image RH201046 in an attempt to resolve the system. This 2.7 ksec observation (not shown) reveals a single bright source spatially coincident with the binary. There are 491 counts within $10''$ of the centroid, at a nominal position of $4^h33^m32.954^s +18^\circ1'3.42''$ (J2000). We rebinned the image to $0.5''$ pixels, and fit the profiles with Gaussians in the X and Y directions. Within the uncertainties the profiles are identical, with FWHMs, respectively, of 3.6 and $3.4''$. The image is noticeably skewed, however. A two-dimensional Gaussian fit gives FWHMs of 3.0 and $3.9''$, respectively, along the minor and major axes. The major axis has a position angle of 49° . The FWHM of the HRI point spread function (David et al. 1997), fit in a similar manner, is $2.9''$. We conclude that there is no evidence that the source is resolved. Since the greatest elongation occurs along an unphysical position angle, we conclude it is likely to be instrumental.

The image also reveals a weak X-ray source (about 20 counts) about $15''$ south of the B stars. This is spatially coincident with the near-IR source HD 28867S.

3.2.2. *Chandra HRC-I*

As a followup to the ROSAT HRI image, we obtained a 4680 sec Chandra HRC-I image (observation 200037). With its $\sim 0.5''$ resolution, this image (Fig. 2) clearly shows a single bright X-ray source. The count rate is 0.33 c s^{-1} . Adopting the Carkner et al. (1996) spectral model, this count rate corresponds to a flux of $3.1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.3-10 keV band. This flux lies within the range of previously observed fluxes. There is no significant variability during this short observation. The source position is coincident to within $0.22''$ with that of HD 28867E (Table 1).

There is no emission evident from the vicinity of West B9 component. Within a $1.32''$ extraction circle, we detect 3.9 ± 2.5 counts, for a count rate of $< 1.5 \times 10^{-3}$ (3σ) . The limiting $\log(L_X/L_{bol})$ of -7.2 is consistent with normal stars of this spectral type.

A weak source was detected within $0.15''$ of the near-IR position of the M star HD 28867S (Table 1). We detected 17 photons from this source, for a net count rate of $3.6 \pm 0.9 \times 10^{-3}$ s $^{-1}$. Assuming a 0.8 keV thermal plasma spectrum, and correcting for $A_V = 0.25$ mag of extinction, the luminosity is about $1.5 \times 10^{29} (D/130 \text{ pc})$ erg s $^{-1}$, and the f_X/f_{bol} ratio is about -2.6. These are consistent with expectations for an active M star.

3.3. Ultraviolet Spectroscopy

We obtained IUE (Boggess et al. 1978) spectra of HD 28867 on 1987 March 10 as part of program TTJFW (Table 3). Three observations, a low dispersion SWP spectrum, and high dispersion SWP and LWP spectra, were taken with the target in the large aperture. The pair is unresolved in the large aperture; the spectra look like those of late-B stars.

We obtained followup SWP-HI spectra in 1994, using the IUE small aperture to separate the two components, as part of program BXPFW. We first centered the star in the FES, slewed to place the light centroid in the small aperture, and then performed blind offsets of the telescope by $+1.5'', -0.25''$ in RA, DEC for the East component, and by $-1.65'', +0.25''$ for the West component. The archival SWP 49847 spectrum is mis-calibrated as a large aperture observation (the script correct labels it as a small aperture observation). We compensated for this by multiplying the calibrated flux by the small-to-large aperture ratio in the file *swpabscal.fit*.

The IUE small aperture has a 3.0 arcsec diameter, so there may be some contamination from the other star, especially if there was some small error in the centroiding or the offset

slews. Based on the FES offsets, the final separation between the two apertures on the sky is $2.7''$, which is less than the true binary separation. The East component appears about twice as bright as the West component in the extracted spectrum, which suggests that either the West component was not well centered in the aperture, or that the East spectrum includes some light from the West component. The summed flux is about half the flux in the large aperture observation, SWP 31968.

The spectra, though noisy, show no gross abnormalities. There are no emission lines, and the absorption lines are consistent with the spectral types. The spectral shapes and line depths of the two stars are very similar. We compared Kurucz (1979) model atmospheres to the spectra in the 1200-1600Å region in an attempt to pin down temperatures. For an assumed $\log g=4$ and $A_V=0.25$, both stars are fairly well described by 10,500K model stars. More detailed analysis is likely to yield unreliable results due to the contamination of the spectra.

3.4. Optical Spectroscopy

We obtained high dispersion optical spectra with the echelle spectrograph on the KPNO 4m Mayall telescope on two occasions. We obtained two spectra on 27 October 1988, with about 1.2 arcsec seeing, some light cirrus at the start of the night, and the moon 4 days past full in Auriga. We used a $1''$ slit oriented E-W with a $4''$ decker length. With one star centered in the slit, the other star was visible at the end of the decker. We extracted the spectra by fitting two Gaussians at each wavelength coordinate, and taking the integral of the Gaussian as the number of counts at that wavelength. The TI2 CCD gave a wavelength coverage of about 5450 to 7200Å. Integration times were 50 and 60 seconds, respectively, for the E and W components.

On 24 January 1997, under excellent seeing conditions, we reobserved the pair. The moon was about 2 days past full, but was below the horizon at the time of the observations. We used the same slit and decker, but off-centered the target near the end of the decker to minimize contamination from the companion. This simplified the reductions. The TK2B CCD provided wavelength coverage from about 4300 to 7400Å. Each star was observed for 5 minutes. Because we used a simple boxcar extraction rather than an optimal extraction, the S/N is limited by pixellation in the image.

We determined the absolute observed wavelength scale using the telluric water vapor lines near $H\alpha$. We then applied the heliocentric correction to establish the wavelength scale.

Segments of the spectra are shown in Figure 3. In each panel the upper trace is the East component while the lower trace is the West component (The central trace is discussed in §4). The West component shows a rotationally-broadened B9 spectrum, with superposed narrow telluric features. The spectra of the East component show prominent broad absorption lines unexpected in a late B star, including Li I $\lambda 6707\text{\AA}$, with an equivalent width of 70 ± 5 mÅ. The strongest of lines (in general, those with $W_\lambda > 30$ mÅ, but excluding broad blends) are tabulated in Table 4. Line identifications are made using the Wallace & Hinkle (1998) Solar atlas, with wavelengths obtained from the Kurucz & Bell (1995) line list. The wavelengths presented in Table 4 are the centroids of the broad and often blended lines measured in the 1997 January spectrum, corrected to heliocentric wavelengths.

Most of the lines are identified with Fe I and Ca I lines prominent in solar-like stars. The lines are broad. A fit to the Li I line gives an equivalent $V \sin i$ of 65 km s^{-1} . Broadening of the other lines is consistent with this.

We measure the radial velocity of the cool star by cross-correlating the spectrum against a template made of the strong lines identified in the spectrum. The radial velocity of the cool star is -5 km s^{-1} in the 1988 observation, and $+29 \text{ km s}^{-1}$ in the 1997 observation,

with uncertainties estimated to be about 2 km s^{-1} . Assuming a γ velocity of 17 km s^{-1} appropriate for the Tau-Aur association, the projected orbital velocity of the cool star must exceed about 22 km s^{-1} .

3.5. Radial Velocity Measurements

Both components of the HD 28867 system were observed with the Coudé feed at Kitt Peak National Observatory on the nights of 9-10 December 1990 and 20 October 1991 as part of an extensive OB star radial-velocity monitoring program. The observing, data reduction, and radial-velocity measurement techniques are described in Morse, Mathieu, & Levine (1991). The configuration for the first run employed the RCA 512x512 CCD detector with the Coude Spectrograph Grating B to provide a dispersion of 0.261 Å pix^{-1} over the wavelength range $3715\text{Å} - 3848\text{Å}$. For the second run the TEK2k CCD was used with Grating B to provide a dispersion of 0.112Å pix^{-1} over $3690\text{Å} - 3860\text{Å}$. Each observation achieved $S/N \sim 40$ per pixel. Both late-type and early-type radial-velocity standard stars (e.g., Fekel 1985) were observed in close temporal proximity to the HD 28867 pair observations.

The heliocentric radial-velocity measurements are based on cross correlations of observed spectra with a grid of Kurucz synthetic template spectra that span a broad range of effective temperature and $v \sin i$. The typical measurement uncertainties reported by Morse et al. (1991) are $\sim 2 \text{ km s}^{-1}$, though 1 km s^{-1} precisions are attained for sharp-lined (low- $v \sin i$) standard stars, such as HR 1149 (B8 III), HR 2010 (B9 IV), and HR 1389 (A2 IV). Their study found that using the Balmer series of lines near 3700Å provided robust results over the spectral type range late-O to early-A for all $v \sin i$'s.

The cross correlation procedure “selects” an appropriate template spectrum by

measuring the quality of the template match using the so-called R value (see Latham 1985). The templates used for the HD 28867 pair measurements were $T_{\text{eff}} = 11,500$ K, $\log g = 4.5$, $v \sin i = 300$ km s $^{-1}$ for the west component, and $T_{\text{eff}} = 10,500$ K, $\log g = 4.5$, $v \sin i = 200$ km s $^{-1}$ for the east component. These stellar parameters should be regarded as first-order estimates, limited by the density of the synthetic template grid, but indicate that the east component is slightly cooler and a somewhat slower rotator than the west component.

The heliocentric radial velocities derived for the west component were +16.3 and +15.6 km s $^{-1}$ for the December 1990 observations and +26.9 km s $^{-1}$ for the October 1991 observation. For the east component, the velocities were +10.3 and +11.9 km s $^{-1}$ for December 1990 and +21.1 km s $^{-1}$ for October 1991. At first sight, one might conclude that both stars are radial-velocity variables, each showing offsets from one observing run to the next that are significantly larger than the nominal measurement precision. The three standard stars mentioned above were observed close in time to the HD 28867 pair observations and show excellent (~ 1 km s $^{-1}$) repeatability. However, during each run the two components are consistently offset from each other by ~ 5 km s $^{-1}$ and the run-to-run offsets for each star are $\sim +10$ km s $^{-1}$.

This behavior makes us wary that there may be some unknown systematic problem with the HD 28867 pair observations, despite the good behavior of the standard stars. We note that Abt & Biggs (1972) and Hoffleit (1982) note that HR 1442 may be a radial velocity variable. Two published values differ by 15 km s $^{-1}$. It is not clear whether these refer to the combined light of the pair, in which case the interpretation is complicated.

3.6. Speckle Imaging

We obtained speckle images of HD 28867 on the evening of 2001 January 12 using the facility IR camera “NSFCam” at the IRTF in non-photometric conditions. We used the $0.055'' \text{ pix}^{-1}$ plate scale to obtain three hundred 0.078 second speckle exposures in each of the J, H and K photometric bands. We used a shift-and-add analysis method to produce the final images. Frames that had less than 30% of the peak flux in the best image were excluded as images that were taken in poor instantaneous seeing conditions. The J, H and K-band images were thus constructed from centroiding and combining the best 169, 207 and 224 frames, respectively.

The speckle image of HD 28867E in the K-band shows only a single source, with a spatial profile indistinguishable from that of HD 28867W (Fig. 4). To estimate limits at which we can detect a companion to HD 28867E, we determined the sensitivity to companions at a range of brightnesses and separations. In Figure 5 we present the sensitivity (ΔK) versus angular separation as derived using HD 28867W as a point spread function calibrator. The sensitivity at the projected separation from the central star is essentially the limiting magnitude at this distance, ten times the standard deviation over the mean counts in each 2 pixel wide annuli. Based on the K-band speckle analysis, we can rule out with confidence a late type companion with a K-band brightness within 1 magnitude of that of the B star at a separation of more than $0.25''$. This corresponds to a projected separation of 32 AU.

A cool companion to HD 28867E will be brighter at the longer wavelengths, so there could be a slight positional shift in the separation between the stars as a function of wavelength. To test this, we measured the spatial separations between the two stellar centroids. There is no significant difference between the separations in the 3 bands, and no trends with wavelength. The mean separation between the centroids in the J, H, and

K band images is $3.070 \pm 0.004''$. The separation between the optical components from the Hipparcos measurements is $3.078 \pm 0.004''$ (ESA 1997). There is no evidence for a significant shift in the centroid position between the optical, where the light from a cool component is insignificant, to the K band.

Formally, the optical and near-IR position angles are significantly different, at a level of $1.00 \pm 0.14^\circ$, corresponding to a northward shift of 0.98 pixels in the East component. However, given the accuracy to which the camera orientation is known, this is probably not significant.

If we accept that the relative shift between the optical and near-IR centroids is no more than one $0.055''$ pixel, then we can put another limit on the maximum separation of the two stars. We show below (§4) that any cool component is roughly as bright as the B star in the K band. A shift in the centroid of $<0.055''$ therefore requires a projected separation $<0.11''$ (14 AU). This is consistent with the speckle sensitivity estimate shown in Figure 5 for $\Delta K=0$ mag.

3.7. Near-IR Spectroscopy

On 29 December 2001 we used the SPEX (Rayner et al 1998; 2002) low resolution spectrograph in the short wavelength, cross-dispersed (SXD) mode, to obtain a spectrum from 0.8 through $2.5 \mu\text{m}$ at a spectral resolution of about 1500. Conditions were photometric. We observed in AB mode, with a $100''$ throw. We observed the brighter East component for 8 minutes (30 second integrations, 2 coadds, 8 AB cycles), and the West component for 12 minutes. We also observed the South component for 16 minutes. We extracted the spectra using the Spextool software version 2.1. We flatten the spectra by assuming that the continua of the A0 stars follow $F_\lambda \propto \lambda^{-4}$ power laws. We then merged

the individual orders into a single spectrum. We used the observed fluxes of the A0 stars, assuming $V - K=0$, to correct to absolute fluxes.

We derive a K magnitude of 6.79 for the West component from the SPEX spectrophotometry. This is within 2% of the photometric magnitude. The derived K magnitude of 6.07 for the East component is 0.1 mag brighter than the photometric magnitude (Table 2). Since there is no evidence for intrusion of light from the (fainter) West component into the slit, the spectra were taken back-to-back, and the calibrations are stable, this may be evidence of variability of the cooler companion. Variability will be small in the optical, where the cool companion contributes only a few percent of the flux.

Spectra of HD 28867E and W are shown in Figure 6. A spectrum of HD 28867S, scaled up by a factor of 10, is also shown in Figure 6. The West component is a good approximation to the Rayleigh-Jeans tail of a blackbody, while the East component has excess flux at long wavelengths. The South component is a good match to an M1 star. This spectral type is consistent with the JHK colors.

The ratio of the flux in the East and West components is shown in the upper trace in Figure 7. The emission in the H I Paschen and Brackett series is an artifact of the division process (the lines are proportionately shallower in the East component, after dilution). The stars were observed consecutively, at airmass less than 2, and most of the telluric absorption features divide out. However, after division there are apparent narrow absorption lines in the flux ratio. Inspection of the spectra shows that they are in absorption in the East component. The absorption features in the K band are identified in Figure 8.

We identified the absorption features by comparison with a Solar IR atlas (Livingston & Wallace 1991). The absorption lines are those of neutral species (Fe I, Si I, Mg I, Na I, Al I), as well as the CO $\Delta\nu=2$ bandheads. This suggests a cool stellar component of spectral type G-K, in good agreement with the optical absorption line spectrum.

4. Spectral Synthesis

On the assumption that HD 28867E is a composite of a late B star and a cool dwarf, we used the near-IR spectrum and an atlas of near-IR spectral standards to estimate the properties of the cool dwarf. We observed the near-IR spectral standards (spectral types G1 through L2) during the same observing run, and with the same instrumental setup.

The radial velocity template and the IUE spectra suggest that HD 28867E is somewhat cooler than HD 28867W. Therefore, we modelled the B star with a range of temperatures, from 1500K cooler than the West component to the same temperature. We used the spectrum of the West component, scaled by the ratio of blackbodies at the two temperatures, as the template for the B star component. We then subtracted this B star model from the spectrum, and fit the difference spectrum, $F_{\text{HD 28867E}} - (F_{\text{HD 28867W}} \times (BB(T)/BB(11,500K)) + F_{\text{standard}})$. At each spectral type, we scale the flux of the standard to match the excess flux, and then subtract the standard. Ideally, the residuals will be uniformly zero for the correct choice of companion.

We determine a best fit companion spectral type from the colors of the difference spectrum, by a χ^2 analysis of the residuals, and by fitting the slope and curvature of the residuals. The best spectral type for a companion with dwarf colors ranges from early-G to mid-K, depending on the assumed temperature of the B star; more luminous companions will have earlier spectral types. In Table 5 we list the derived parameters of the companion over the tested range of B star temperatures. The spectral type is determined by comparison with the spectral energy distributions of the IR standards. The radius is derived from the flux normalization. The magnitudes in Table 5 have been corrected for $A_V=0.25$ mag. In addition, we present the ratios of the B star to companion flux in the R_C and K bands. The range of possible locations of the companion in the H-R diagram is shown in Figure 9.

Note that this analysis considers only the broadband spectral energy distribution,

and not the information in the spectral lines. We generated synthetic optical spectra by adding the spectrum of HD 28867W (the B9 template) and G-K spectra diluted by the appropriate factor (see Table 5). Prior to adding the spectra, we added a Li I line with an equivalent width corresponding to a cosmic abundance $\log n(\text{Li})=3.3$ (Pavlenko & Magazzu 1996), appropriate for a PMS star, and then smoothed the spectrum to approximate a rotational broadening $V \sin i=65 \text{ km s}^{-1}$. The middle traces in Figure 3 show this synthetic spectrum for a G2 companion. It successfully reproduces the broad spectral lines, including Li I $\lambda 6707\text{\AA}$, in the spectrum of HD 28867E. By visual inspection of these composite spectra, we were able to exclude a companion as late in spectral type as K5, but we cannot distinguish between a G2 and K0 companion. The increase in the spectral dilution in the cooler stars almost exactly compensates for the deepening lines, and the rapid rotation washes out all but the strongest features, which are not strongly sensitive to temperature in this range

The lower trace in Figure 7 shows the ratio of the observed flux from HD 28867E to this synthetic spectrum in the near-IR. The spectral energy distributions match, as do the lines in the K band. In particular, the $\Delta\nu = 2$ CO bandheads and the $\lambda 2.21\mu\text{m}$ Na I doublet and $\lambda 2.26\mu\text{m}$ Ca I triplet go into emission (are undersubtracted) if we force the companion spectral type later than about K0.

Greene & Meyer (1995) and Hodapp and Deane (1993) have quantified relations between various absorption line indices and T_{eff} or spectral type. Prior to measuring the lines, we accounted for telluric absorption by dividing the spectrum by the normalized spectrum of an A0 star observed at the same air mass. The equivalent widths of the Na I doublet and the Ca I triplet in the difference spectrum depend on the selected temperature differential. Even after correcting for the telluric absorption, the continuum is not well defined, and lines are blended, at this resolution. The summed equivalent width (Greene

and Meyer’s atomic index) range from 2.5Å for a 1500K temperature differential to 3.0Å for no differential. This corresponds to spectral type K0V to K2III, which is slightly cooler than indicated by the broadband spectral energy distribution or the optical lines. The CO bandheads subtract well for late-G spectral types; the gravity dependence of the CO bandheads permit stars as cool as early-to-mid K for luminosity class III (see Figures 8 and 10 of Hodapp & Deane 1993).

5. Conclusions

We conclude that this star does not support the premise that late-B stars can be intrinsically luminous X-ray sources. HD 28867E is a composite of a late B star and a cooler PMS star.

This conclusion is based on optical and near-IR spectroscopy, as well as the near-IR photometry. The spectroscopic data limit the spectral type of the companion to between about G0 and K0, with the spread due to the uncertainty of the temperature of the B star component. Uncertainties in the reddening cannot affect the shape of the near-IR spectral energy distribution sufficiently to affect this conclusion. One can refer to the location of the companion in the H-R diagram (Fig. 9) to draw further conclusions. There we show the location of the star referenced to evolutionary tracks and isochrones from Baraffe et al. (2002) and D’Antona & Mazzitelli (1994). The Baraffe et al. tracks use a mixing length equal to the pressure scale height and $Y=0.275$; the D’Antona & Mazzitelli tracks are those using mixing length convection and Alexander opacities. Note that the tracks and isochrones differ. The Baraffe et al. tracks incorporate more recent input physics, but are lacking above $1.4 M_{\odot}$. From the Baraffe et al. tracks, we can conclude that the mass exceeds about $1.2 M_{\odot}$, and that the age, at least at the red end of the allowable range, is 1-3 Myr, consistent with the age of the Tau-Aur T association. The D’Antona

and Mazzitelli tracks permit a younger and less massive star. For reference, the open circle shows the location of HD 283572, one of the brightest low mass PMS stars in Taurus.

For a temperature difference of 1000K, the spectrophotometric deconvolution leaves a hot component with $V=6.92$ and $V - K=0.03$ (unreddened). This star is 0.13 mag fainter than the West component. Using the simple relations that the V band flux will be proportional to R^2T , that $R \sim M$, and that $T \sim M^3$, where R , T , and M are respectively the stellar radius, mass, and temperature, we expect a star 1000K cooler than the West component to be about 14% fainter. This consistency adds confidence to our spectrophotometric deconvolution.

The X-ray and radio emission is fully consistent with this interpretation of the system as a B star and a cooler companion. The IRAS $12\mu\text{m}$ flux is inconsistent with this, as it overestimates the flux, extrapolated from K by λ^{-4} , by a factor of 4. This could be attributable to a circumstellar disk around one or both of the stars. The disk would need to have a substantial inner hole, as it does not appear to contribute significantly in the K band.

With the data in hand, we can start to constrain the orbit of the system (assuming this is no chance projection). The cool star is brighter than the B star in the K band so long as the spectral type is earlier than K0 (Table 5). The 14 AU limit from the K band imaging is a limit for the semi-major axis for circular orbit. The system is unlikely to be oriented pole-on. The $\sim 65 \text{ km s}^{-1}$ line width constrains the rotation period to be less than 2.0 ($R/2.6 R_{\odot}$) days. This is consistent with the rotation periods of the more massive of the low mass PMS stars, and suggests that the inclination i exceeds about 30° (corresponding to a 1 day rotation period). If the rotation and orbital axes are coaligned, this i applies to the binary system as well. No evidence has been reported for an optical eclipse, so the inclination must be less than 90° , but this is not a strong constraint since the semi-major

axis is likely to be large compared to the stars.

A B9 star has a mass of about $3 M_{\odot}$. It is unfortunate that the B star radial velocity measurements are inconclusive, since for reasonable secondary masses ($>0.5 M_{\odot}$) the radial velocity of the B star should vary by $>4 \text{ km s}^{-1}$. For orbital inclinations $i > 30^{\circ}$, and $0.5 < M_2/M_{\odot} < 2.0$, the semi-major axis of the system lies between about 0.8 and 4.7 AU (6 – 36 mas), and the orbital period lies between about 4 months and 5.5 years. All these values are overestimates, given that we only have a lower limit on the orbital $V \sin i$ of the secondary.

Further observations will throw more light on this system. We have renewed our efforts to determine the radial velocities of the B stars in the HD 28867 pair using the echelle spectrograph at the ARC 3.5-m telescope. High dispersion spectra in the red and near-IR can be used to determine the orbit of the cool companion, and high dispersion, high S/N spectra in the near-IR will yield better limits on the spectral type. Diffraction-limited K-band imaging on a larger telescope may be able to directly resolve the system. We have hopes that in the near future this system will be one of the few astrometric and spectroscopic binaries among the pre-main sequence stars, and hence an important calibrator for stellar evolution models.

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Fig. 1.— The inner $1'$ of the CIRIM K band image. HD 28867 is the bright pair in the center. HD 28867S, an early M star, is $15''$ to the south. The scaling is linear.

Fig. 2.— The central part of the Chandra HRC-I image. The data have been binned into $0.26''$ pixels. The three circles mark the relative positions of the three stars. The circles have radii of $1''$. The axes are labeled in arcsec from HD 28867E.

Fig. 3.— Segments of the optical spectra. In each panel, the upper trace is the spectrum of HD 28867E, the lower trace is the spectrum of HD 28867W, and the thick trace in the center is the composite spectrum made by summing the spectrum of HD 28867W with an appropriately scaled and broadened spectrum of the G2V star HD 211476. A Li I $\lambda 6707\text{\AA}$ line corresponding to $\log n(\text{Li})=3.3$ has been added. All spectra are normalized to their median; the upper and lower spectra in each panel are offset by ± 0.1 units, respectively. The scalloping visible in the HD 28867W spectrum, prominent in the upper panel, is an artifact of the data extraction. The narrow lines near $\lambda 6475$ are telluric H_2O .

Fig. 4.— The speckle image in the K band from the IRTF. The scaling is logarithmic above a level of about 3 times the sky. The stellar cores are sharp, and the image is clearly diffraction-limited. The plate scale is $0.055'' \text{ pix}^{-1}$.

Fig. 5.— The sensitivity, ΔK , versus separation as determined using HD 28867W as a point spread function calibrator. We should have easily detected any companion to HD 28867E that had a separation and brightness lying below the sensitivity curve.

Fig. 6.— Near-IR spectra obtained with SPEX. The upper trace is the East component; the middle trace is the West component. The lowest trace is the South component, an M star. The flux scale is absolute, except that the flux of the South component has been increased by a factor of 10 for display purposes. The East component is significantly brighter than the West component in the near-IR. We have not corrected for telluric absorption.

Fig. 7.— Near-IR flux ratios. The upper trace is the ratio of the flux in the East component to that in the West component. There is a clear cool excess relative to the B9 continuum. The apparent emission in the H I Brackett and Paschen lines is attributable to continuum veiling. The lower trace is the ratio of the East component to the composite B9+G2 spectrum described in the text. The continua are well matched, as are most spectral features.

Fig. 8.— The E/W flux ratio in the K band. Prominent absorption features are indicated. The H I Br γ emission is an artifact of the division, but the absorption lines are real features. The CO bandheads and the neutral absorption are consistent with a G star spectrum.

Fig. 9.— Hertzsprung-Russell diagrams showing the allowable locations of the cool companion. The vertical bars mark, from left to right, the inferred position for the East B star 1500, 1000, 750, 500, 250, and 0 K cooler than the West component. The vertical extent of the allowable region reflects the ± 23 pc uncertainty in distance from the Hipparcos parallax. The open circle denotes the location of HD 283572. The tracks in the lower plot are from Baraffe et al. (2002); those in the upper plot are from D’Antona & Mazzitelli (1994), using mixing length convection. Baraffe et al. do not provide models for more massive stars. The isochrones are not directly comparable at ages less than a few million years. Evolutionary tracks are labelled in solar masses; isochrones are labeled in units of 10^6 years. Although the inferred masses and ages differ, it is clear that the cool companion is young and fairly massive.

Table 1. J2000 Positions of HD 28867

Star	RA	DEC	V	source
HD 28867E	4 33 33.049	18 01 00.20	6.99	Hipparcos
HD 28867W	4 33 32.835	18 01 00.58	7.04	Hipparcos
HD 28867S	4 33 32.806	18 00 43.61		
radio source	4 33 33.023 (.002)	18 01 00.47 (.02)		White et al. 1992
X-ray source (E)	4 33 33.06 (.01)	18 01 00.3 (.1)		Chandra HRC-I
X-ray source (S)	4 33 32.81 (.01)	18 00 43.5 (.1)		Chandra HRC-I

Table 2. near-IR Photometry

Star	Aperture ($''$)	K	$J - K$	$H - K$
HD 28867W	1.9	6.81 ± 0.02	0.04 ± 0.03	0.08 ± 0.04
HD 28867E	1.9	6.17 ± 0.02	0.22 ± 0.03	0.12 ± 0.04
HD 28867 E+W	12.6	5.69 ± 0.02	0.12 ± 0.03	0.09 ± 0.04
HD 28867S	7.8	9.64 ± 0.05	0.91 ± 0.08	0.20 ± 0.07

Table 3. IUE observations

Star	Camera	Image	Aperture	time (sec)	Date
HD 28867 E+W	SWP-HI	31967	Large	1080	1987 March 10
HD 28867 E+W	SWP-LO	31968	Large	24	1987 March 10
HD 28867 E+W	LWP-HI	11796	Large	600	1987 March 10
HD 28867W	SWP-HI	49847	Small	9600	1994 January 19
HD 28867E	SWP-HI	49851	Small	10200	1994 January 20

Table 4. Narrow Optical Absorption Features

Observed Wavelength	W_λ (mÅ)	ID	True Wavelength
5447.2	118	Fe I	5446.575/5446.916
5456.3	56	Fe I	5455.441/5455.609
5463.7	55	Fe I	5463.271
5477.5	60	Fe I/Ni I	5476.287/5476.563/5476.900
5481.9	31	Fe I/Ti I	5480.864/5481.242/5481.429/5481.438
5488.7	33	Fe I	5487.763
5498.1	36	Fe I	5497.516
5507.2	44	Fe I	5506.778
5513.2	32	Ca I	5512.980
5529.0	33	Mg I	5528.405
5545.8	76	Fe I	5543.147/5543.937 + 5546.500/5546.991
5555.1	34	Fe I	5553.594/5554.882
5570.2	35	Fe I	5569.618
5573.5	51	Fe I	5572.841
5576.8	31	Fe I	5576.090
5582.7	25	Ca I	5581.965
5587.5	45	Fe I	5586.756
5595.0	37	Ca I/Fe I	5594.462/5594.654
5599.1	30	Fe I/Ca I	5598.289/5598.480

Table 4—Continued

Observed Wavelength	W_λ (mÅ)	ID	True Wavelength
5603.5	48	Fe I/Ca I	5602.767/5602.842/5602.945
5616.1	58	Fe I	5615.644
5625.2	42	Fe I	5624.038/5624.542
5641.9	31	Fe I	5641.436
5655.6	46	Fe I	5655.183/5655.489
5659.1	65	Fe I	5658.531/5658.816
5683.3	52	Ni I/Na I	5682.198/5682.633
5712.5	34	Fe I/Ni I	5711.850/5711.883/5712.131
5753.9	62	Fe I/Ni I	5752.023/5753.121/5754.655
5763.4	34	Fe I	5762.990
5816.8	23	Fe I	5816.367
5858.2	34	Ca I	5857.451
6008.8	39	Fe I	6008.554
6066.0	30	Fe I	6065.482
6079.2	30	Fe I	6078.491/6078.999
6103.4	55	Fe I/Ca I	6102.173/6102.723/6103.186
6122.6	48	Ca I	6122.217
6137.6	82	Fe I	6136.615/6136.993/6137.694
6142.4	41	Fe I	6141.730

Table 4—Continued

Observed Wavelength	W_λ (mÅ)	ID	True Wavelength
6162.7	73	Ca I	6162.173
6170.2	62	Ca I/Fe I	6169.042/6169.563/6170.504
6191.7	42	Ni I/Fe I	6191.171/6191.558
6220.0	47	Fe I	6219.279
6231.3	57	Fe I	6230.726
6247.0	61	Fe I	6246.317
6259.1	23	Ti I	6258.709
6265.0	52	Fe I	6265.131
6336.9	70	Fe I	6336.823
6394.2	32	Fe I	6393.602
6400.7	71	Fe I	6400.000
6408.4	41	Fe I	6408.016
6412.1	36	Fe I	6411.647
6421.3	53	Fe I	6421.349
6439.6	41	Ca I	6439.075
6450.4	54	Ca I	6449.808
6456.7	41	Ca I	6455.598
6463.2	48	Ca I	6462.567
6496.0	290	Ca I/Fe I	λ 6495Å blend

Table 4—Continued

Observed Wavelength	W_λ (mÅ)	ID	True Wavelength
6500.0	43	Ca I	6499.650
6547.1	43	Fe I	6546.245
6594.0	21	Fe I	6593.871
6634.3	41	Fe I	6633.746
6644.2	50	Ni I	6643.629
6664.0	91	Fe I	6663.5
6678.6	47	Fe I	6677.909
6708.4	75	Li I	6707.8
6718.0	33	Ca I	6717.681
6734.1	52	Fe I	6733.151
6821.0	68	Fe I	6820.369
6843.8	104	Fe I	6842.679, 6843.648

Table 5. Companion Parameters

T_{Bstar} (K)	SpT	radius (R_{\odot})	V (mag)	K (mag)	$\frac{F_B}{F_{comp}}$ (at R_C)	$\frac{F_B}{F_{comp}}$ (at K)	IR standard
10,000	G1	2.6	8.4	6.6	2.6	0.69	HD 27836 (G1V)
10,500	G2-G5	2.7	8.8	6.7	3.7	0.83	HD 6582 (G5V)
10,750	G5-K0	2.8	8.7	6.8	3.6	0.92	—
11,000	K0-K2	2.9	9.1	6.8	4.9	1.00	HD 112758 (K0V)
11,250	K2-K5	3.2	9.6	6.9	7.6	1.11	HD 4628 (K2V)
11,500	K5-K7	3.4	10.1	6.8	10.9	1.06	HD 97503 (K5V)



































